

*The Electrical Qualities of Porcelain, with special reference to
Dielectric Losses.*

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The following research was undertaken to determine some of the electrical properties of porcelain, and their variations with respect to potential, temperature, and time.

The electrical properties investigated in this paper are as follows :—

A. Capacity Measurements.

1. The rate of charge of a porcelain condenser.
2. The charge of a porcelain condenser as a function of the potential.
3. The influence of sudden cyclical changes of potential on the charge of a porcelain condenser.
4. The dielectric constant of porcelain as a function of the temperature, and its value.

B. Conductivity Measurements.

5. The apparent conductivity of porcelain as a function of the potential.
6. The apparent conductivity of porcelain as a function of the time of electrification.
7. The apparent conductivity of porcelain as a function of the temperature, and its value.

C. Dielectric Loss Measurements.

8. Contact method, variable frequency, and constant potential.
9. Thermo-electric method: Constant frequency, variable potential.
10. Thermo-electric method: Variable frequency, constant potential.
11. Historical.
12. Summary.

Material.—The porcelain was in the form of glazed discs, about 21 cm. in diameter and 0·55 cm. thick, from the Fabrik Hermsdorf, Sachsen-Altenburg. The discs had a circular tinfoil electrode of 20·5 cm. diameter fixed on them on each side.

Instruments.—Current readings were taken with a Siemens and Halske galvanometer, the usual sensibility of which was about $0\cdot5 \times 10^{-10}$ ampere

per millimetre deflection at 2 metres. The deflections were read by means of a telescope and scale, and could be estimated to $1/10$ mm.

Batteries.—For potentials up to 200 volts a battery of 100 large accumulators was used. For potentials up to 5000 volts a battery of 2500 small accumulators was used. These cells were made up in sections of 50 in two rows of 25 each, fixed into a paraffin wax base which rested on a glass plate backed with wood. Contact was made with mercury cups.

1. The rate of charge of a porcelain condenser.

Two plates connected in parallel were used, and they were charged and discharged by means of a paraffin wax insulated mercury switch.

To secure accuracy, and to avoid temperature and other effects, the following method was adopted:—

(1) The plates were charged for one second, and were then discharged through the galvanometer, the swing being noted.

(2) They were then charged for two seconds, discharged, and the swing noted. The plates were discharged for a time equal to, or greater than, the charge time.

About 70 of these double readings were taken, the charges of one and two seconds alternating. The averages of these results were then calculated, and from their difference the percentage increase of charge, when the charge time was increased from one to two seconds, was calculated.

The charging voltage was also noted, and then we have two points on the time-charge curve for this particular voltage.

The plates were then charged for two and three seconds in the same manner, then for three and four seconds, four and six seconds, etc.

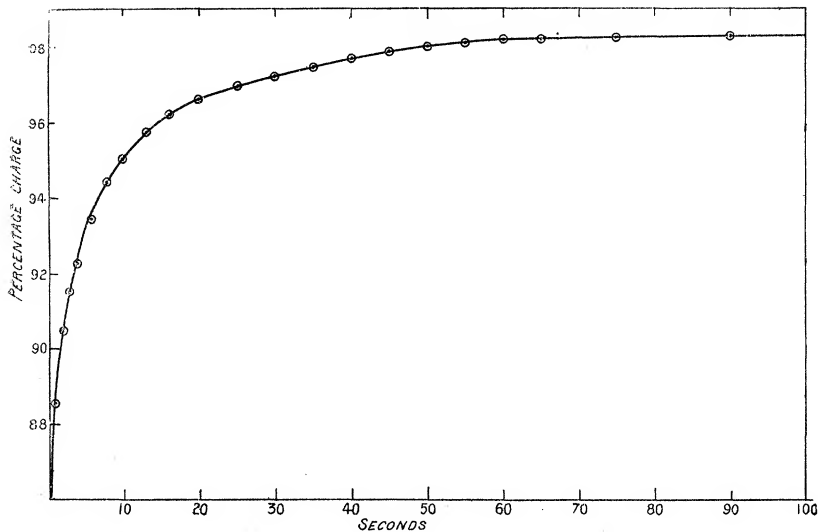
It was assumed in this experiment, and proved in the next, that the potential charge curve for porcelain was a straight line, therefore the time-charge curve may be continued, and the charge for three seconds calculated for the original voltage.

The curve was continued in this manner up to 30 minutes' charge. Beyond 90 seconds a slight increase of the charge will be noted, for this may be due to a temperature effect; practically the porcelain is fully charged in one minute, if we take the first galvanometer swing as a measure of the capacity. The results are graphically represented in Curve 1, and numerically in Table I.

In the 20 and 30 minute charges the readings varied somewhat, it was thought on account of temperature changes; so some rough temperature readings were taken, and the variations in swing were reduced to percentages per degree centigrade, the average result being 1.9 per cent.

Table I.

Charge time, seconds.	Percentage charge.	Charge time, seconds.	Percentage charge.
1	88.58	35	97.41
2	90.50	40	97.62
3	91.54	45	97.82
4	92.29	50	97.96
6	93.44	55	98.07
8	94.45	60	98.11
10	95.08	65	98.13
13	95.79	75	98.26
16	96.21	90	98.26
20	96.60	600	98.68
25	96.95	1200	99.57
30	97.15	1800	100.00



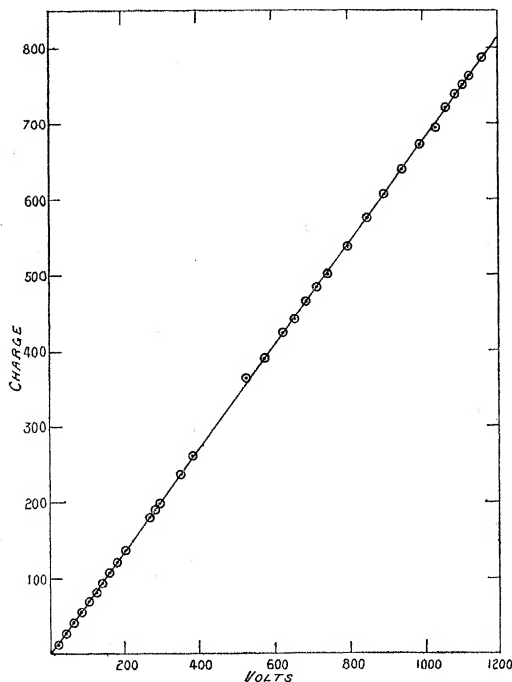
CURVE 1.—Charge of a Porcelain Condenser as a Function of the Time of Charge.

2. The charge of a porcelain condenser as a function of the potential.

The two plates used in the previous experiment were charged for half a minute, discharged for one minute, and the swing of the galvanometer and the potential were noted.

Readings up to 200 volts were taken in steps of 20 volts, and 40 readings were taken at each voltage. Temperatures were noted at the beginning, middle, and end of each series, and a rough estimate of the percentage variation of charge per degree centigrade was made; it was about 2.3 per cent. Up to 200 volts the points lie along a straight line, and any small variations from it followed the temperature variations.

The potential charge curve was now constructed, using the high-tension battery up to 1200 volts. The results are plotted in Curve 2, and from it will be seen that the charge is directly proportional to the charging potential. This agrees with J. Curie's work on crystals,* in which he found that the charging current is exactly proportional to the potential when the potential changes are slow. It will be seen later that this does not hold if the changes are rapid.

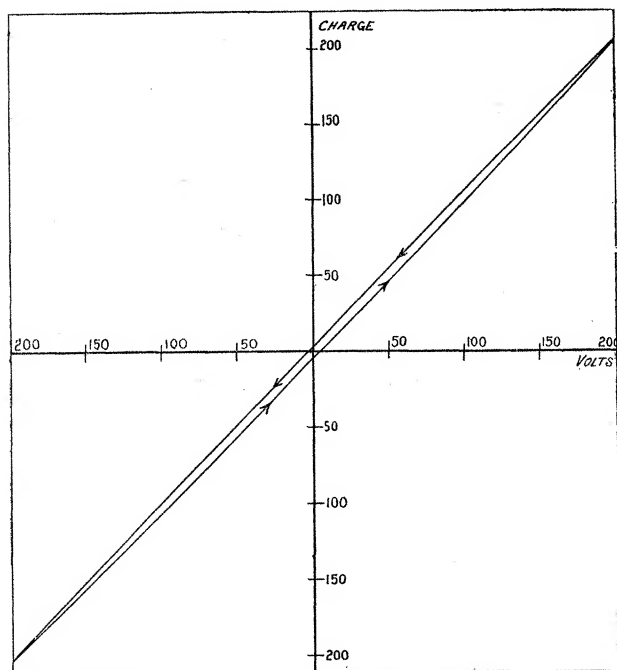


CURVE 2.—Potential-Charge Curve for Porcelain Condenser.

3. The effect of sudden cyclical changes of voltage on the charge of a porcelain condenser was now investigated.

Three plates were enclosed in a vessel, containing phosphoric acid as drying agent, and were charged, and discharged, for one minute in the usual manner. The charging potential was altered by approximately 40 volts each time between limits ± 200 volts. Several cycles were gone through, and the charge was plotted against potential in Curve 3. The descending values are slightly greater than the ascending ones, thus showing a small dielectric loss even with very slow rates of change of the field. This point is dealt with more fully under the heading "Dielectric Loss."

* J. Curie, 'Thèse de Doctorat,' June, 1888.



CURVE 3.—Potential-Charge Curve for Porcelain Condenser, Potential varied cyclically.

4. The variation of the dielectric constant with temperature was investigated in the following manner :—

Three porcelain plates were placed in a copper vessel containing a drying agent. This copper vessel was heated by means of an oil bath, the oil of which was first heated to the required temperature by a Bunsen burner. The temperature was then maintained constant by means of an electric heater, which consisted of a framework of asbestos insulated iron wire wound on the inner copper vessel. The heat radiation from the apparatus was exactly balanced by the current sent through the resistance framework.

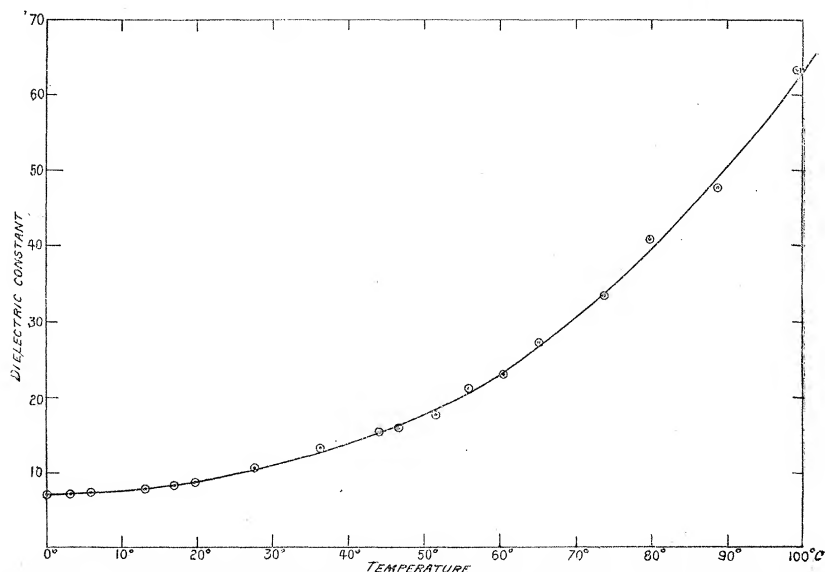
The oil was circulated by means of a pump and stirrers worked by hand.

The temperature was measured by a thermometer resting on the porcelain. The porcelain was charged and discharged in the usual manner, charge and discharge being each of one minute's duration, the potential being reversed each time to neutralise polarisation effects. The charging and discharging was continued until the galvanometer swings and temperature were constant for at least one hour.

The results of the experiment are given in Table II, and are graphically shown in Curve 4.

Table II.

Temperature, °C.	Dielectric constant.	Temperature, °C.	Dielectric constant.
0·38	7·22	46·66	16·00
3·44	7·48	51·59	17·95
5·93	7·53	55·93	21·20
13·17	7·95	60·50	23·00
16·52	8·60	65·00	27·30
19·92	8·95	73·89	33·20
27·55	10·82	79·88	40·80
36·22	13·40	88·56	47·50
44·04	15·50	99·00	63·50



CURVE 4.—The Dielectric Constant of Porcelain as a Function of the Temperature.

From the results it will be seen that the temperature has a very great influence on the dielectric constant.

At temperatures 0° to 30° C. the increase of capacity is much smaller than at higher temperatures. Between 0° and 30° the capacity increases 54 per cent. (0·0006 microfarad), and between 70° and 100° it increases 108 per cent. (0·0052 microfarad), being a nine times as great a rate of growth. From 0° to 30° the dielectric constant is a quadratic function of the temperature, the equation being of the form—

$$C_t = C_0(1 + 0·00223t + 0·0005t^2).$$

where

C_t = dielectric constant at temperature t

and

C_0 = dielectric constant at zero temperature.

From 30° to 100° the equation of the curve is

$$C_{t_1} = C_{t_2} e^{0.0264(t_1 - t_2)},$$

where C_{t_1} = dielectric constant at temperature t_1

and C_{t_2} = " " " t_2 .

From Table II, and the above equation, we find that the dielectric constant for this kind of porcelain at 20° C. is 8.95.

B. Apparent Conductivity Measurements.

By the apparent conductivity is meant the conductivity as expressed by the ratio of current to potential.

5. The apparent conductivity of porcelain as a function of the potential.

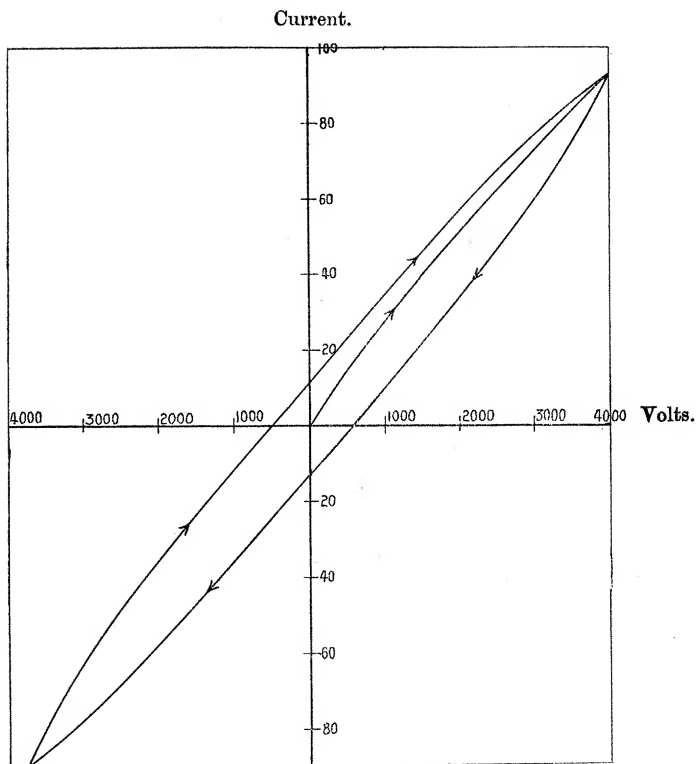
A porcelain plate was placed in an air-tight glass vessel containing a drying agent, and a current was sent through it as well as through the galvanometer from the high-tension battery. At the end of 1½ minutes the deflection was noted, and from it the conductivity per centimetre cube was calculated.

The potential was increased by steps of 110 volts to 2500 volts; the current curves obtained were concave towards the voltage axis, but they did not remain constant, they varied daily. The conductivity decreased greatly with increase of potential.

On taking the readings with decreasing potentials the results obtained were widely different from those obtained with increasing potentials, and on putting the porcelain through a cycle of electrification the curve obtained for current with respect to the potential formed a closed curve as shown in Curve 5.

On putting the porcelain through a number of continuous cycles of electrification the same curve was traced out each time, thus showing that a steady cyclical state had been reached. The porcelain, on having a potential impressed on it, generates a back E.M.F. which varies for different cycles of electrification. In other words the dielectric becomes polarised.

If we consider the dielectric as being made up of electric doublets (particles of matter having electric poles), they are normally in a heterogeneous condition, but when an electrostatic field is impressed on the dielectric, the particles tend to orientate with their electrical axes along the lines of force. The number which would do so would vary directly with the impressed voltage, and their electrostatic potentials would add up to resist the flow of current through the dielectric. The free poles of the particles in contact with the electrodes would constitute the charge.

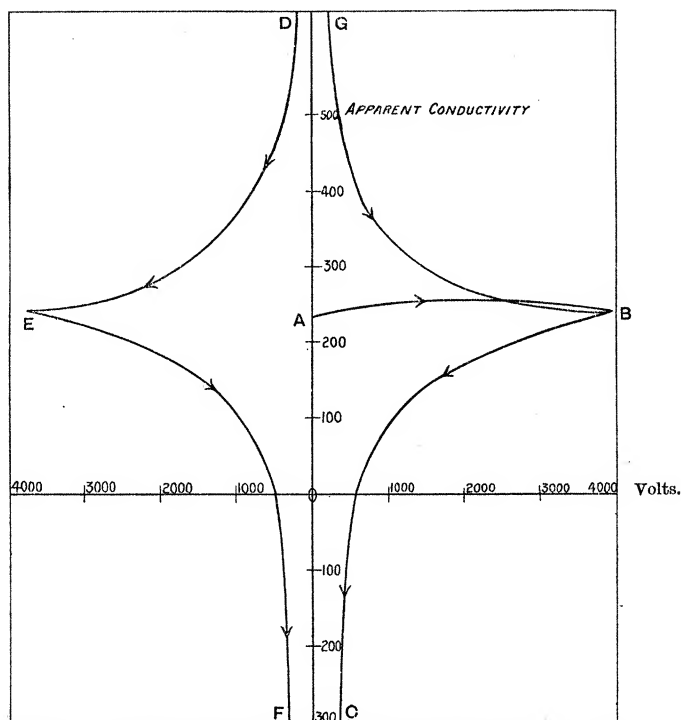


CURVE 5.—The Current-Potential Curve for Porcelain, the Potential being varied cyclically.

On Curve 6 the apparent conductivity is plotted with respect to the potential. It will be noticed that on starting with an unpolarised dielectric, the conductivity is fairly constant for increasing potentials (A to B), but on decreasing the potential the conductivity rapidly falls owing to the polarisation of the dielectric (B to C), and the fact that the curve goes off to a negative infinity simply means that the back E.M.F. of the porcelain is greater than the impressed E.M.F. The curve starts again from $+\infty$ on account of the back E.M.F., then assisting the forward E.M.F. The conductivity then decreases more slowly (D to E), reaching a fairly level value at the position of maximum E.M.F., and on decreasing the E.M.F. it goes through a negative infinity again (E to F), starting again from positive infinity (G).

A similar curve would be obtained if we plotted the reluctance of an iron circuit against the magnetomotive force.

Current voltage curves were plotted for cycles ± 4000 , ± 3000 , and ± 2000 volts with similar results.



CURVE 6.—Apparent Conductivity-Voltage Curve for Porcelain.

The back E.M.F.'s for zero current, *i.e.* the points where the curves cut the voltage axes, were as follows:—

±4000 volts curve.....	+550 and -540 volts,
±3000 „ 	+450 „ -420 „
±2000 „ 	+340 „ -320 „

It will be noticed that the positive values are always greater than the negative ones. The averages of these back E.M.F.'s bear the following relationship to one another:—

$$V_{b4000} : V_{b3000} : V_{b2000} :: 1.65 : 1.31 : 1.00.$$

The back E.M.F. is not proportionate to the voltage applied. It would seem as if the number of doublets coming into line per unit fall of potential was decreasing, or in other words the permeability of the dielectric decreases with increase of electrification, or the dielectric tends towards electrical saturation.

The currents with no applied voltage, *i.e.* the points where the curves cut the current axis, were as follows:—

±4000 volts curve.....	+12.0 and -12.5 volts,
±3000 „ 	+11.0 „ -12.0 „
±2000 „ 	+ 8.0 „ - 9.0 „

The negative values are greater than the positive ones. The current due to the polarisation of the dielectric does not increase proportionately to the amplitude of the cycle but varies with the back E.M.F.

The currents at ± 4000 , ± 3000 , and ± 2000 volts were :—

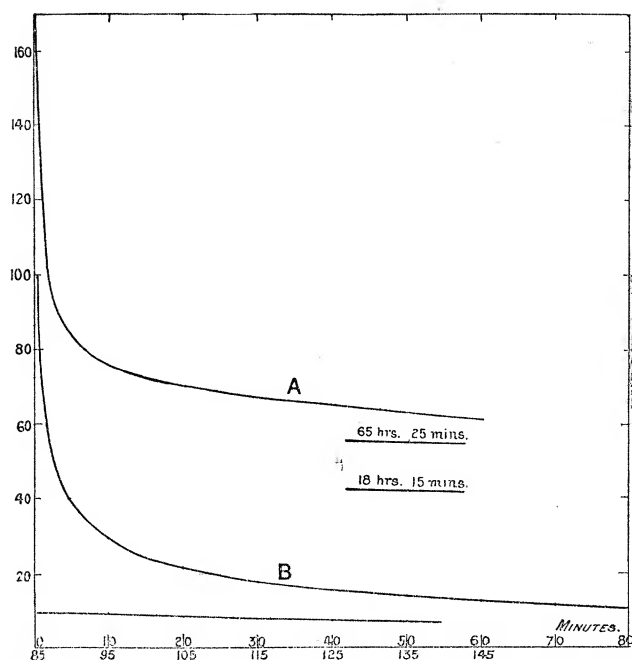
C_{4000}	+93 and -98,
C_{3000}	+80 „ -88,
C_{2000}	+54 „ -56.

The apparent conductivity increases with decrease of voltage. The negative values here are greater than the positive, the sum of these variations being that the current curves are depressed slightly into the negative quadrants.

6. The variation of the apparent conductivity of porcelain with the time of electrification was now investigated.

Fifteen plates, connected in parallel, were placed in a glass vessel containing a drying agent and a thermometer. The plates were placed in a pile on porcelain feet and were connected in parallel with strips of tinfoil. The glass vessel was sealed up with paraffin wax, and the connecting wires were brought out through long glass tubes filled with paraffin wax. Current was supplied by a battery of 100 cells, the voltage being constant (200) throughout the experiment.

The apparent conductivity plotted against the time gave Curve 7 (A), from which it will be seen that the conductivity falls very rapidly in the first 10 minutes, and then more gradually for an hour. After 18 hours the conductivity was considerably smaller than at the end of the first hour, and after 65 hours the conductivity had an intermediate value. This was probably a temperature effect. After 65 hours 35 minutes the electrodes were short-circuited through the galvanometer; a large current was given in the reverse direction which was much greater than the positive current measured before switching the cells off. This was not the ordinary capacity discharge, as the galvanometer was short-circuited while this was taking place. This current was measured every minute for over two hours, and it fell in the same manner as the current produced by the applied E.M.F. fell. The results are shown graphically in Curve 7 (B); they indicate that the dielectric takes a very considerable time to polarise completely, and that in doing so it stores up energy which may afterwards be returned. The cycle is reversible, the porcelain dielectric acts like an accumulator. From the above result it would appear that the current voltage loops of the previous experiment would alter with the time of the cycle, turning in a clockwise



CURVE 7.—A. Conductivity of Porcelain as a Function of the Time of Electrification.
B. Short Circuit Current from Porcelain.

direction with increased time of the cycle on account of the lower conductivity due to the increase of polarisation with time. This point was investigated with the 15 plates and the 200-volt battery.

The voltage was raised or lowered by steps of 40 volts each time. The time of the step in the first series was one minute, for the second series two minutes, for the third series three minutes, fourth series five minutes, fifth series seven minutes.

The curves flatten out and turn in a clockwise direction as the time of the cycle increases.

The areas of the loops bear the following ratio to one another:—

$$A_1 : A_2 : A_3 : A_5 : A_7 :: 171 : 146 : 126 : 122 : 100.$$

The maximum currents bear the following ratio:—

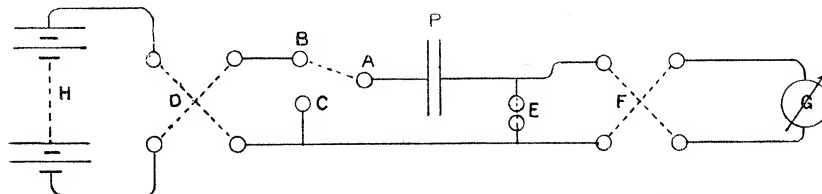
$$C_1 : C_2 : C_3 : C_5 : C_7 :: 158 : 150 : 141 : 120 : 100.$$

The apparent conductivity has decreased with the increased time of the cycle, thus showing viscosity in the conducting mechanism.

7. The conductivity of porcelain as a function of the temperature.

Fourteen porcelain plates were placed in a pile in the inner copper vessel used in the previous temperature experiment, with phosphoric acid as drying

agent. The heating arrangements were as before, but the oil was maintained at a uniform temperature by an inclined propeller driven by a small motor. The plates were connected in parallel by strips of tinfoil, and the terminals consisted of two mercury cups into which dipped glass tubes which passed through air-tight holes in the cover of the vessel. The mercury excluded air from the vessel, and contact was conveniently made with the porcelain by dipping wires into the mercury. Leakage was tested for by just lifting the wires out of the mercury and noting the deflection. In all cases, however, the leakage was practically *nil*. The top and bottom porcelain plates had no electrodes and simply served as insulators. The connections were as follows :—



H. Charging battery. D. Battery reversing switch.
E. Galvanometer short-circuiting switch.
F. Galvanometer reversing switch.
P. Porcelain.

A B C. Charging and discharging switch.

By connecting A to B current was sent through the porcelain, and by connecting A with C the porcelain was discharged.

The conductivity was measured after one minute's electrification by opening the short-circuiting switch E and noting the first swing.

The porcelain was then discharged for four minutes to get rid of polarisation; the battery and galvanometer connections were reversed, and the conductivity was again measured with the reversed potential. At each reading the temperature of the porcelain was noted, and when both galvanometer swing and temperature had been steady for at least one hour, the average of these readings was taken and the conductivity calculated. The porcelain was usually heated for five or six hours before taking the final readings, as it took a long time to reach a steady electrical state corresponding with a steady temperature.

The results of the experiment are given in Table III and Curve 8. It will be seen that the increase of conductivity with temperature is very great. The following is the equation for the curve:—

$$\gamma_{t_1} = \gamma_{t_2} \cdot e^{0.090837(t_1 - t_2)},$$

where

 γ_t = conductivity at temperature t_1

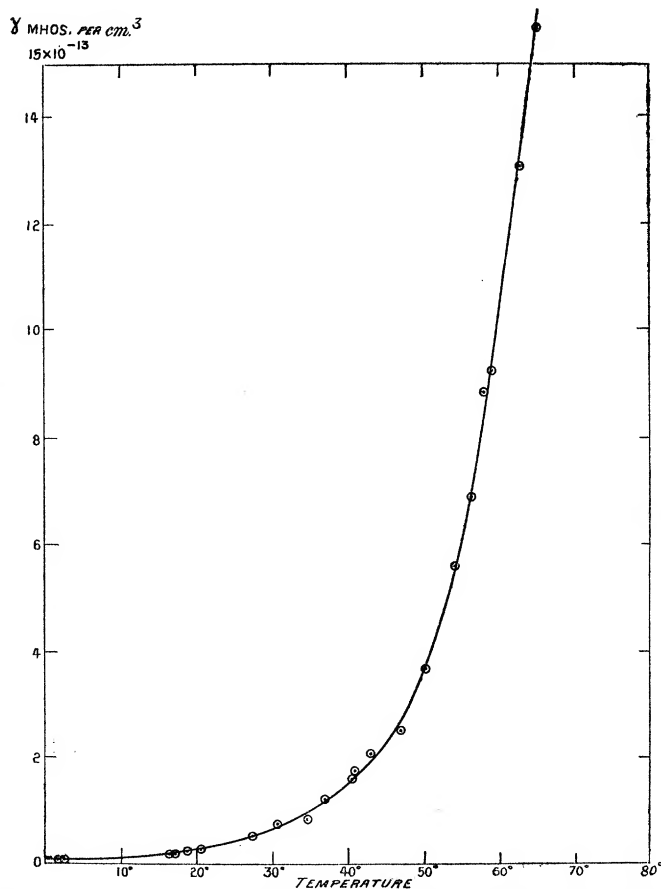
and

$$\gamma_{t_0} = \quad , \quad t_2.$$

From Table III and the above equation the specific conductivity of porcelain, calculated at 20° C., was 0.2624×10^{-13} mhos per centimetre cube.

Table III.

Temperature, ° C.	Specific resistance, ohms per cm. ³	Temperature, ° C.	Specific resistance, ohms per cm. ³
1.63	143.0×10^{12}	40.86	5.70×10^{12}
2.10	141.0 "	43.03	4.85 "
16.40	51.5 "	47.00	4.01 "
17.00	50.8 "	50.40	2.64 "
18.65	42.3 "	54.01	1.78 "
20.50	35.5 "	56.51	1.44 "
27.32	20.0 "	58.04	1.11 "
30.87	14.0 "	59.12	1.08 "
34.70	11.8 "	62.72	0.77 "
37.03	8.24 "	64.89	0.64 "
40.62	6.25 "	81.93	0.15 "



CURVE 8.—Apparent Conductivity of Porcelain as a Function of the Temperature.

$$\gamma_1 = \gamma_2 \cdot e^{0.090837(t_1 - t_2)}$$

C. The Dielectric Loss.

8. The foregoing results show that there is a loss of energy in putting a porcelain condenser through a cycle of electrification, and it is desirable to find on what factors this loss depends and the laws connecting it with variations of voltage, frequency, and temperature. Another point which suggests itself is: Does the capacity of the condenser alter under electrostatic pressure, and if so, how?

To investigate the dependence of the dielectric loss on the frequency of the cycle of electrification, the following experiments were made:—

A porcelain plate was placed in a sealed glass vessel, with sulphuric acid as drying agent, and was connected across the secondary of a transformer giving about 2000 volts. The current and voltage waves were then plotted with the Joubert contact method. The area of the current wave was then calculated for different values of the time, and so the quantity of electricity on the condenser was obtained for that time, $Q = \int idt$.

The voltage at this time was known from the voltage curve, and Q was plotted against V . The resultant curve enclosed an area similar to Curve 3. The area of this curve represents the energy required to put the condenser through a cycle of electrification at that particular frequency and voltage.

A number of these curves were constructed at various frequencies, and the results are given in Table IV. These results seem to show that the loss per cycle is roughly a constant quantity. Results 7, 8, and 9 vary considerably from the average. This may be due to errors of measurement, also the process of obtaining the final loss curve is rather a complicated one, and errors could easily creep in.

Table IV.

Cycles per second.	$V_{\max.}$	Loss per cycle. Joule 10^{-4} .	Temp., ° C.
Part I (for whole plate).			
107	3000	8.83	22.4
114	2760	8.30	23.5
130	2680	9.45	19.8
140	3060	7.80	20.8
150	2950	9.55	20.0
160	2960	9.20	22.1
170	3020	14.8	20.6
180	2685	29.8	18.9
190	3000	12.3	18.5
200	2960	9.45	20.3
Part II.			
110	2580	5.5	
125	2640	4.98	
150	2500	4.57	
175	2580	5.57	
225	2600	7.58	

To investigate these points further, the following method was adopted, which could be worked more rapidly, and by one person alone, whereas the previous method required two observers.

The porcelain plate was placed in a large glass case containing some strong sulphuric acid. Pressure was supplied with a Ferranti transformer, transforming from 150 to 40,000 volts.

In series with the porcelain condenser was placed a condenser of large capacity (C_1) compared with that of the porcelain (C_2), and a non-inductive resistance of 40,000 ohms. The current through the porcelain was measured by measuring the voltage across the resistance, and the voltage across the porcelain was measured by the same instrument (an Ayrton and Perry Quarter Cylinder Electrometer) being placed across part of a non-inductive resistance, which itself was placed across the primary of the transformer (see diagram of connections). Connection to the bottom electrode of the porcelain was made through the brass case of the thermopile. The current passing had no effect on the thermopile.

It was intended to measure the capacity of the porcelain (C_2) by measuring the pressure across the condenser (C_1) placed in series with it, according to the law $C_1V_1 = C_2V_2$, where V_1 being small the capacity C_1 could be assumed to remain constant, but on connecting the condenser C_1 to the electrometer a small deflection was first obtained which rapidly grew larger until it was beyond the range of the electrometer. It was found that this deflection was due to polarisation, for, when a battery was placed in series with the electrometer, the deflection always increased when the negative pole of the battery was connected with the earthed side of the condenser, thus showing that the polarising current was passing through, or over, the porcelain from low to high tension side. It was thought that perhaps the brush discharge was causing this effect, so an earthed guard ring was put round the bottom electrode, but the result was the same. This condenser was then dispensed with, and capacity calculations were made from the values of the current, voltage, and frequency. This was allowable as the E.M.F. wave was a pure sine wave.

A considerable alteration had to be made in the apparatus on account of the large quantities of ozone and oxides of nitrogen which were formed by the brush discharge, and which rendered the rooms very objectionable to work in. The porcelain plate was placed on one end of a thermopile (used for temperature measurements), the whole standing in a large photographic dish, and was covered with a bell-jar.

Air was sucked into the apparatus through two towers containing calcium chloride, and a wash-bottle containing sulphuric acid (see diagram of

apparatus). The bell-jar was sealed at the bottom with ordinary machine oil. The ozonised air was led out through a tower containing manganese dioxide (to split the ozone up into oxygen), and a wash-bottle containing strong sulphuric acid, to prevent any water vapour from creeping into the apparatus. The air current was produced by an ordinary filter pump, and the air was dried before entering the apparatus, in order to diminish the brush discharge.

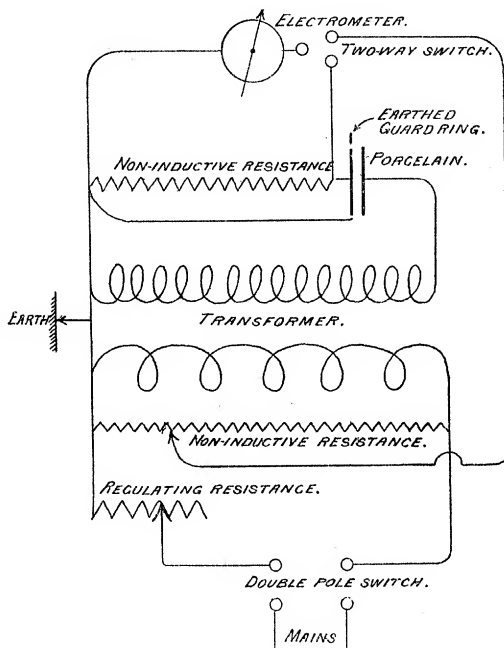


Diagram of Connections.

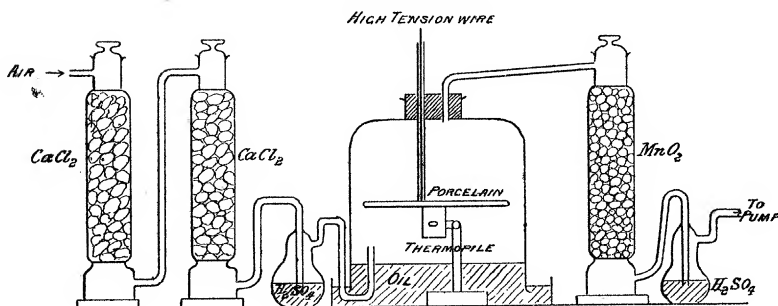
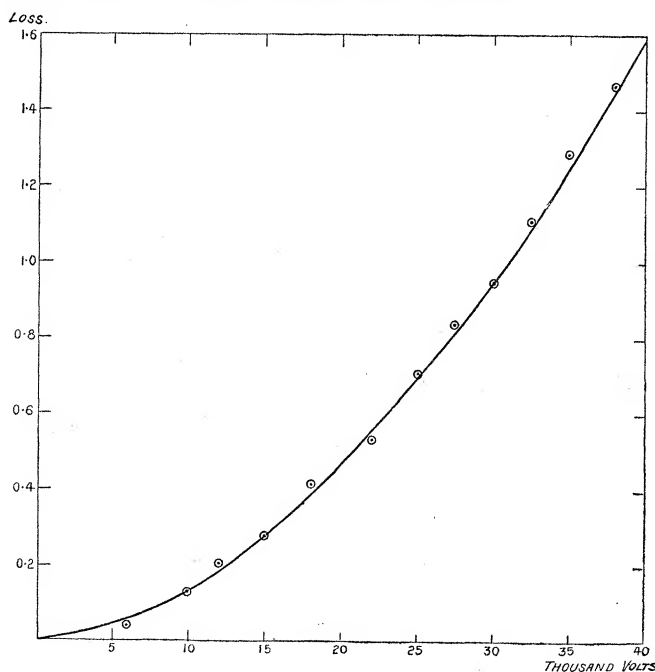


Diagram of Apparatus.

The dielectric loss was measured by the difference of temperature which could be maintained by the centre of the surface of the porcelain plate above atmospheric temperature. This temperature difference being only a

few degrees, it follows from Newton's laws of cooling, that the heat lost is proportional to this difference; and as the heat lost is equal to the heat gained, if the temperature is constant, a thermopile placed with one end in contact with the porcelain will generate an E.M.F. which is directly proportional to the dielectric loss. This E.M.F. was measured by connecting the thermopile with a low resistance galvanometer through a reversing switch, and noting the direct and the reversed deflections to neutralise the effect of local E.M.F.'s, etc. The losses were first measured at a constant frequency of 50 per second, with pressures up to 38,000 volts (R.M.S.). The results are graphically represented in Curve 9. The equation to the curve is expressed by

Loss per cycle $\propto kV_{\text{R.M.S.}}^{1.74} = 1.83 \times 10^{-12} V^{1.74}$ Joule per cubic centimetre, where V is the R.M.S. potential gradient per centimetre.



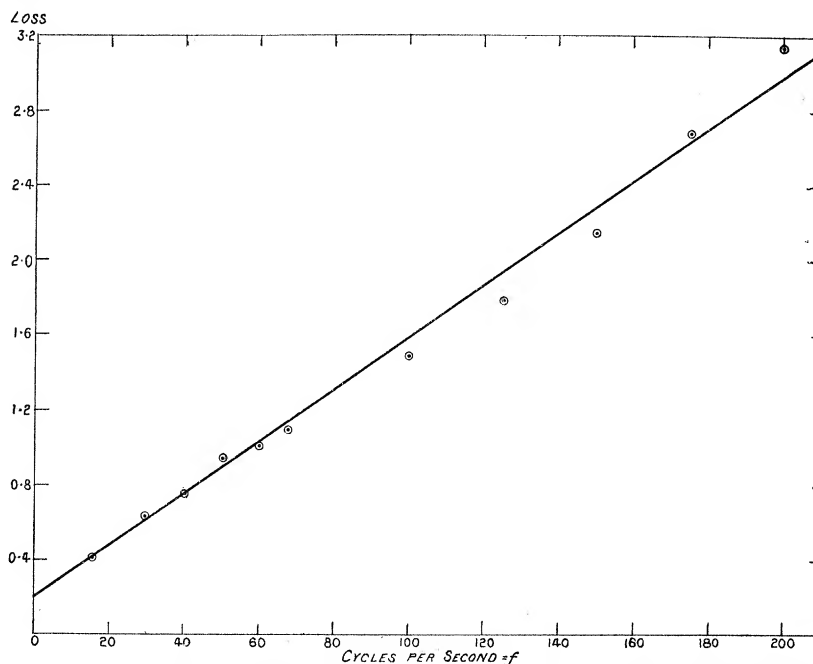
CURVE 9.—Potential-Loss Curve for Porcelain. Frequency Constant = 50.
Loss $\propto KV^{1.74}$.

The losses were then determined at constant pressure (30,000 volts), and for frequencies between 15.8 and 200.

The points obtained lie practically on a straight line which does not pass through the origin (Curve 10), so we have the equation for the dielectric loss as follows:—

$$\left. \begin{array}{l} \text{Dielectric loss per cubic} \\ \text{centimetre in time } t \end{array} \right\} = 1.83 \times 10^{-12} V_{\text{R.M.S.}}^{1.74} (f + 14.4) t \text{ Joules,}$$

where V is the R.M.S. potential gradient per centimetre and f is the number of cycles per second.



CURVE 10.—Frequency-Loss Curve for Porcelain. Voltage Constant = 30,000 R.M.S.
 $\text{Loss} \propto 0.0139 f + 0.2$. $K = 0.000655$ mfd.

The constant 14.4 is probably due to the fact that porcelain is not a perfect insulator, and that a certain current would flow if a direct pressure of 30,000 volts was applied to it, giving rise to an ordinary C²R loss.

We have here a striking similarity between magnetic and dielectric losses. They are each independent of the time in which the cycle is completed (if we neglect the C²R loss due to the imperfection of the dielectric), and are proportional to similar powers of the amplitude of the cycle.

May we not extend this similarly to the internal actions? Let us imagine the dielectric to consist of electric instead of magnetic doublets: these particles would oscillate or revolve under the influence of an alternating electric field, and energy would be absorbed in overcoming their molecular friction.

Dielectric Losses. Historical.

In 1861, W. Siemens published a paper on the heating of the glass of a Leyden jar,* and pointed out that a condenser became heated on charge and discharge. Many attempts have been made to measure the loss of energy in dielectrics subjected to a varying electric field.

* 'Monatsber. d. Berlin Akad.,' October, 1861.

In 1890, J. Swinburne suggested* that the loss was due to want of homogeneity in the dielectric, and imagined conducting channels to run across the dielectric, giving rise to a C²R loss. This view has been accepted by many subsequent investigators. In 1891, Major Cardew† attempted to measure the power factor of a paraffined paper condenser by the "Three Voltmeter" method, but the results obtained are doubtful.

In the same year Hutin and Leblanc,‡ working with paraffined paper condensers, also attributed the loss to heterogeneity of the dielectric, and came to the conclusion that they were dealing with the case studied by Poisson of a perfect dielectric, containing many small spheres of conducting material. They destroyed the fibre of the paper by strongly heating, and in doing so the dielectric constant fell from 8 to 2.56. The condenser then stood 1000 volts per centimetre without heating, but at higher pressures the temperature rose.

Steinmetz,§ experimenting on paraffined paper condensers, found the dielectric loss to vary as the square of the applied pressure. The pressures used varied between 80 and 320 volts at 170 ~; at higher pressures he found that the loss increased at a higher power than the square of the applied pressure. Steinmetz pointed out the analogy between the hysteresis loss in iron and dielectric loss, and so the name "Dielectric Hysteresis" was loosely given to any kind of dielectric loss.

Janet|| makes a similar remark, and says that solid dielectrics present phenomena quite analogous to magnetic hysteresis, in consequence of which, at equal pressures, the charge in a condenser is smaller for increasing than decreasing pressures.

Janet, in a later account,¶ experimenting on a mica condenser, obtained a curve enclosing an area for the relation between charge and P.D. analogous with a magnetic cycle in iron, but its form may be accounted for by hysteresis, or viscosity, or both.

By a hysteretic loss we mean one which is independent of the time taken for the cycle, and this point has been overlooked by many experimenters.

Hess** agrees with Poisson in his case of a perfect dielectric containing conducting spheres, and deduces theoretically the existence of residual charge, and dielectric loss, and shows that the loss would agree with the results of

* 'Phys. Soc. Proc.,' vol. 11, p. 49.

† 'I. E. E. Proc.,' May, 1891.

‡ 'La Lumière Électrique,' vol. 41, p. 179, July, 1891.

§ 'Electrical Engineer' of New York, March 16, 1892.

|| 'Comptes Rendus,' December, 1892.

¶ 'Comptes Rendus,' vol. 116, p. 373, February, 1893.

** 'La Lumière Électrique,' vol. 46, p. 402, November, 1892.

Steinmetz and others. Hess does not think that the result obtained by Steinmetz, $P=KE^2$ for dielectrics, can be considered as analogous to his law for magnetic hysteresis, $P=KB^{1.6}$, because, if dielectric hysteresis existed, it would be entirely swamped by the C^2R loss due to the conducting bodies.

Arnot* suspended hollow cylinders of various substances in a rotating electric field, and showed that the cylinders had a tendency to turn; from this, Arnot calculated the energy expended in the dielectric, and called the loss hysteretic, although he might just as easily have attributed it to viscosity.

Bedell, Ballantyne and Williamson† employed a method similar to the one described on p. 234, and attributed the loss to hysteresis.

Porter and Morris,‡ using very slow cycles of electrification, found the variation in charge of a condenser for equal pressures, on increasing or decreasing the potential, to be less than one in eight thousand, and so concluded that the effects were due to viscosity rather than hysteresis.

F. Beaulard§ found that the energy dissipated in different dielectrics at different frequencies varied with the time of the cycle, and tended to vanish as the time of the cycle increased. According to him, the loss was a viscous one.

E. E. Northrup|| shows that the value of the specific inductive capacity of a dielectric is larger for a slowly varying field than for a rapidly varying field.

Experiments of Blondlot and J. J. Thomson¶ show even greater changes.

H. Pellat** tried to show that the energy loss was due to dielectric polarisation, and states†† that if a solid or liquid dielectric be suddenly placed in an electric field it polarises, the polarisation increasing with time, and tending to a maximum. If the field ceases, the polarisation diminishes to zero.

W. Schaufelberger‡‡ suspended ellipsoids of ebonite and paraffin bifilarly between the plates of a Kohlrausch condenser, and found the energy loss from the increased damping of the oscillations. In the case of paraffin the loss was proportional to the square of the field strength. Arnot found that they varied as the 1.8th-power of the field.

The following methods have also been adopted to determine the losses in dielectrics:—

* ‘Rendiconti R. Accad. Lincei,’ October 16, 1892; ‘The Electrician,’ vol. 30, p. 516, March 3, 1893; ‘La Lumière Électrique,’ vol. 46, p. 536, December, 1892.

† ‘Physical Review,’ vol. 1, p. 81, October, 1893.

‡ ‘Roy. Soc. Proc.’ vol. 54, p. 7, May, 1893; and vol. 57, p. 468, March, 1895.

§ ‘Journ. de Physique,’ August, 1900, pp. 422—437.

|| ‘Phil. Mag.’ vol. 39, pp. 78 and 95, June, 1896.

¶ ‘Recent Researches in Electricity and Magnetism,’ p. 471, etc.

** ‘Annal. Chim. Phys.’ vol. 18, pp. 150—181, October, 1899.

†† ‘Comptes Rendus,’ vol. 128, pp. 1218—1220; also pp. 1312—1314, 1899.

‡‡ ‘Wied. Ann.’ vol. 67, No. 2, pp. 307—324, 1892.

Kleiner* used a thermo-couple embedded in the dielectric.

Bermischke† used a bolometer to determine the rise in temperature in a paraffin wax plate, but failed to detect any, and concluded that dielectric hysteresis did not exist. He attributed the losses to (1) Joule effect, (2) residual charges (viscosity), (3) mechanical losses due to vibration of condenser sheets.

Rowland and Penniman‡ used the split dynamometer method brought out by Professor Rowland; they experimented on paraffined paper condensers, and found the loss to increase with the frequency of the cycle. In other experiments they found that the loss per cycle was independent of the time of the cycle. These results are opposite to those of Porter and Morris, and it seems not unlikely that, under certain conditions, viscosity may be the predominating feature of the dielectric, and, under other conditions, hysteresis.

Rosa and Smith§ using a resonance method in conjunction with a wattmeter, found that the loss was proportional to the square of the current, and hence the loss might be attributed to the equivalent resistance of the condenser. The voltage varied from 400 to 2250, and the condenser was of paraffined paper.

Dr. P. Humman|| using the resonance wattmeter method with different kinds of cables, found that the loss was proportional to V^2 .

Summary.

1. A porcelain condenser charges at a comparatively slow rate (Curve 1). This may account for the dielectric constant, as measured by alternating current, being smaller (7.18 at 14°3 C.) than that measured by continuous current (8 at 14°3 C.).

2. For pressures up to 1200 volts the charge was directly proportional to the pressure, if the potential changes were made slow enough (Curve 2).

3. If the potential changes were made rapidly, the charge was not quite proportional to the potential. There was a certain dielectric loss (Curve 3).

4. The dielectric constant, measured after one minute's electrification varied with the temperature according to the following laws:—

Between 0° and 30° C. $C_t = C_0 (1 + 0.00223t + 0.0005t^2)$,

Between 30° and 100° C. $C_{t_1} = C_{t_2} \cdot e^{0.0264(t_1 - t_2)}$.

The dielectric constant at 20° was 8.95 (Curve 4).

* 'Wied. Ann.,' vol. 50, p. 138.

† 'Wiener Sitzber.,' No. 102, vol. 7, p. 1345.

‡ 'Phil. Mag.,' vol. 45, p. 66, 1898.

§ 'Phys. Review,' vol. 8, p. 4, January, 1899.

|| 'Inaug. Diss.,' Bonn, 1896, Extract, "El. Zeitschr.," 1898, pp. 435—436.

5. The apparent conductivity of porcelain varies with the applied pressure and the duration of the application. The dielectric polarises, or generates a back E.M.F., when a potential difference is applied to it (Curves 5 and 7).

The conducting mechanism shows viscosity.

6. The apparent conductivity of porcelain, measured after one minute's electrification, increases with the temperature according to the following law:—

$$\gamma_{t_1} = \gamma_{t_2} \cdot e^{0.090837 (t_1 - t_2)} \text{ (Curve 8).}$$

The specific conductivity at 20° C. is

$$0.2624 \times 10^{-13} \text{ mhos per centimetre cube.}$$

7. The dielectric loss varies as the 1.74th-power of the voltage (Curve 9), and is independent of the time of the cycle. The dielectric loss at high pressures and reasonable frequencies may be termed hysteretic. At very slow frequencies the loss is mainly C²R loss, and this shows viscosity effects; but these losses are swamped at working frequencies by the dielectric hysteresis (see Curve 10).

The dielectric constant is not affected by the electrostatic pressure, or by the frequency of the alternation of the electrostatic field, within the limits of the experiment.

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